

# Constraints on the presence of water megamaser emission in $z \sim 2.5$ ultraluminous infrared starburst galaxies

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## ABSTRACT

We present Expanded Very Large Array and Arecibo observations of two lensed submm galaxies at  $z \sim 2.5$ , in order to search for redshifted 22.235 GHz water megamaser emission. Both SMM J14011+0252 and SMM J16359+6612 have multi-wavelength characteristics consistent with ongoing starburst activity, as well as CO line emission indicating the presence of warm molecular gas. Our observations do not reveal any evidence for H<sub>2</sub>O megamaser emission in either target, while the lensing allows us to obtain deep limits to the H<sub>2</sub>O line luminosities,  $L_{H_2O} < 7470 L_{\odot}$  ( $3\sigma$ ) in the case of SMM J14011+0252, and  $L_{H_2O} < 1893 L_{\odot}$  for SMM J16359+6612, assuming linewidths of 80 km s<sup>-1</sup>. Our search for, and subsequent non-detection of H<sub>2</sub>O megamaser emission in two strongly lensed starburst galaxies, rich in gas and dust, suggests that such megamaser emission is not likely to be common within the unlensed population of high-redshift starburst galaxies. We use the recent detection of strong H<sub>2</sub>O megamaser emission in the lensed quasar, MG J0414+0534 at  $z = 2.64$  to make predictions for future EVLA C-band surveys of H<sub>2</sub>O megamaser emission in submm galaxies hosting AGN.

*Subject headings:* galaxies: submillimeter - galaxies: starburst - cosmology: observations

## 1. Introduction

An important goal for our understanding of galaxy formation and evolution is to quantify the state of the molecular gas (mass, temperature, and density) available to form stars

in young galaxies. Despite many years of study at submm-to-cm wavelengths, very few observational probes of the molecular gas in high-redshift starburst galaxies and active galactic nuclei (AGN) have emerged. Most efforts have focused on observations of redshifted CO line emission, demonstrated to be an effective tracer of the total molecular gas reservoir available to form stars in nearby ultraluminous infrared galaxies (e.g. Downes & Solomon 1998). Searches at high-redshift have successfully detected CO line emission in more than 60 galaxies (e.g. Solomon & Vanden Bout 2005), where most have been selected for their luminosity at far-infrared wavelengths, indicating the presence of heavy elements. High dipole moment molecules such as HCN and  $\text{HCO}^+$  have been detected in the most luminous objects within this CO-selected sample (Solomon et al. 2003; Vanden Bout et al. 2004; Wagg et al. 2005; Riechers et al. 2006). These high-density gas tracers have proven very difficult to detect in high-redshift objects, as they are typically an order of magnitude fainter than the corresponding CO line emission.

Megamaser emission from the OH and  $\text{H}_2\text{O}$  molecules may serve as a powerful alternative means of studying the dense gas in high-redshift objects (see Lo 2005 for a review). Generally associated with star-formation or AGN activity, strong OH or  $\text{H}_2\text{O}$  megamaser emission could be detected at frequencies,  $\nu \lesssim 10$  GHz using current facilities. The luminosity in the OH maser line has been demonstrated to correlate strongly with FIR luminosity (Darling & Giovanelli 2002), while a weak correlation may also exist between the FIR luminosity and that in the 22 GHz water megamaser line (Castangia et al. 2008). Surveys for both molecular species in strongly lensed quasars and submm galaxies (hereafter SMGs) have been conducted (Wilner et al. 1999; Ivison 2006; Castangia et al. 2008; Edmonds et al. 2009). The first detection of  $\text{H}_2\text{O}$  megamaser emission at a cosmologically significant distance was in a type-II QSO at  $z = 0.66$  by Barvainis & Antonucci (2004). More recently, Impellizzeri et al. (2008) have detected  $\text{H}_2\text{O}$  megamaser emission in the lensed quasar, MG J0414+0534 at  $z = 2.639$ . The discovery of such megamaser emission in a quasar existing when the Universe was about 20% of its present age, opens up the possibility that megamaser (or kilomaser) emission may also be detectable in equally luminous, star-forming galaxies at these early times.  $\text{H}_2\text{O}$  masers are observed towards star-forming regions in the Milky Way, and indeed have been detected in a few nearby starburst galaxies (e.g. Haschick & Baan 1985; Henkel, Wouterloot & Bally 1986; Hagiwara, Diamond & Miyoshi 2002, 2003; Nakai, Sato & Yamauchi 2002). Extragalactic  $\text{H}_2\text{O}$  megamasers with isotropic luminosities,  $L_{\text{H}_2\text{O}} > 10 L_\odot$ , are confined to the nuclei of galaxies, where the physical conditions needed to reach population inversion, namely temperatures above 300 K and densities greater than  $10^7 \text{ cm}^{-3}$ , are more likely to be present.

Among the most luminous class of high-redshift starburst galaxies are the submm galaxies (SMGs), discovered in blank-field submm/mm-wavelength bolometer surveys with single-

dish telescopes (Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Bertoldi et al. 2000). These typically have  $850\ \mu\text{m}$  flux densities,  $S_{850\mu\text{m}} \gtrsim 5\ \text{mJy}$ , implying FIR luminosities,  $\gtrsim 10^{13}\ L_{\odot}$  (assuming a greybody distribution with dust temperature,  $T_d = 40\ \text{K}$  and  $\beta = 1.5$  describes the FIR-to-mm emission). Optical spectroscopic surveys have published redshifts for less than 100 SMGs (e.g. Chapman et al. 2003, 2005). These surveys have been hindered by the coarse angular resolution of submm/mm telescopes, so that deep radio interferometry has been needed to identify the correct multi-wavelength counterparts, and also by the faintness of the optical/infrared counterparts (e.g. Wang et al. 2007). An alternative method has been to use broad bandwidth mm-to-cm wavelength receivers in searching for redshifted CO line emission (Wagg et al. 2007; Daddi et al. 2009a, b). These searches have so far been moderately successful in obtaining redshifts for  $z > 3.5$  SMGs. Lower frequency searches for redshifted megamaser and gigamaser emission may prove to be a viable alternative to searches for molecular CO line emission in SMGs (Townsend et al. 2001; Ivison et al. 2006; Edmonds et al. 2009), with telescopes like the Expanded Very Large Array (EVLA)<sup>1</sup>. Such observations could also provide an effective means of probing the dense gas in these objects, since previous searches for HCN emission in SMGs have not been successful (Carilli et al. 2005; Gao et al. 2007). In this study, we present EVLA and Arecibo observations of H<sub>2</sub>O megamaser emission in two gravitationally lensed SMGs. Throughout this work, we assume  $H_0=71\ \text{km s}^{-1}$ ,  $\Omega_M=0.27$ , and  $\Omega_{\Lambda}=0.73$  (Spergel et al. 2007).

## 2. Targets

The two SMGs in our sample were discovered in submm surveys of low redshift galaxy clusters, where gravitational lensing has been used to constrain the faint end of the submm/mm source counts ( $S_{850\mu\text{m}} < 2\ \text{mJy}$ ; e.g. Smail, Ivison & Blain 1997; Knudsen et al. 2008). Both sources have also been previously detected in CO line emission, so that the emission redshift of the molecular gas region is known with sufficient accuracy to conduct further searches for redshifted H<sub>2</sub>O megamaser emission within the narrow spectral bandwidth afforded by the current VLA correlator.

Previous studies have observed H<sub>2</sub>O megamaser emission in high-redshift AGN, whereas our sample is comprised of purely starburst galaxies. SMM J14011+0252 at  $z = 2.565$  (Barger et al. 1999) was discovered in the  $850\ \mu\text{m}$  SCUBA survey of the A1835 cluster field (Ivison et al. 2000), and subsequently detected in CO  $J=3-2$  line emission by Frayer et al.

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(1999). The lensing amplification factor of this source has been the subject of some debate, and may be as high as  $\sim 25$  (Downes & Solomon 2003; Motohara 2005; Smail et al. 2005; Smith et al. 2005), however in this analysis we adopt a lower factor of 3.5 (Smail et al. 2005) so as to be conservative in our derived luminosity limits in the case of a non-detection. The optical spectral characteristics of this SMG are consistent with that of a starburst galaxy (Frayer et al. 1999), while the mid-IR spectrum is also consistent with no AGN being present in this SMG (Rigby et al. 2008). Our second target, SMM J16359+6612 is a  $z = 2.517$  SMG lensed into three components by the A2218 cluster (Kneib et al. 2004), with the brightest component lensed by a factor of  $\sim 22$ . All three components have been detected in CO line emission (Sheth et al. 2004; Kneib et al. 2005), revealing a mass in molecular gas of only  $\sim 3 \times 10^9 M_{\odot}$ . Non-detections of SMM J16359+6612 in both the 0.5–2 and 2–8 keV *Chandra* X-ray bands imply that no obscured AGN is present, a conclusion supported by the mid-IR spectrum of SMM J16359+6612, which is similar to a starburst galaxy template derived from  $z \sim 0$  galaxies (Rigby et al. 2008).

### 3. Observations and data reduction

The rest frequency of the H<sub>2</sub>O maser line is 22.23508 GHz, so that at the redshifts of our two targets ( $z \sim 2.5$ ; Table 1), the extended frequency coverage provided by the new EVLA C-band receivers (4–8 GHz) is required to conduct our search. Observations of SMM J16359+6612 were obtained in two five-hour tracks on September 28 and 29, 2008 (project AW750). A total of 16 EVLA antennas were available during a move from the compact D to the most extended A configuration. Another five-hour track in the B configuration was observed toward SMM J14011+0252 on February 17, 2009 (project AW761), when 18 EVLA antennas were available. In both cases, the central tuning frequency was dictated by the redshift of the high- $J$  CO lines detected previously in these two sources (Frayer et al. 1999; Sheth et al. 2004). A bandwidth of 6.25 MHz was used to cover the velocity range of the CO lines, and a spectral resolution of 97.656 kHz was adopted.

Flux density and bandpass calibration were performed using observations of 3C286, while we observed 1642+689 as a phase calibrator for SMM J16359+6612, and 1354-021 for SMM J14011+0252. The data were reduced using the NRAO’s Astronomical Image Processing System (AIPS). Table 1 summarizes our EVLA observation parameters.

We have also observed J14011+0252 with the 305 m Arecibo radio telescope<sup>2</sup>, in order to

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<sup>2</sup>The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

search for H<sub>2</sub>O megamaser emission at a frequency of 6.237 GHz. These data were obtained during 3.5 hours of observing on March 12 and 13, 2009, with the C-high receivers and using the standard ‘ON/OFF’ observing mode. Both orthogonal polarizations were recorded. Five minutes were spent in each of the ‘ON’ and ‘OFF’ positions during a single scan. The correlator was configured to provide 64 channels of spectral resolution, and the final rms per channel is 152  $\mu$ Jy/beam after hanning smoothing. These observations are  $\sim 20\%$  more sensitive than our EVLA observations of the same source. The data were analyzed using standard Arecibo Observatory *idl* routines.

#### 4. Results

Our C-band spectra of SMM J14011+0252 and SMM J16359+6612 do not reveal any evidence for H<sub>2</sub>O line emission. Given the strong lensing amplification of these objects by foreground galaxy clusters, our spectra can be used to derive very deep limits to the line luminosities of any H<sub>2</sub>O megamasers which may be present. Following Edmonds et al. (2009), we first correct the spectrum extracted at each of the three components of SMM J16359+6612 for its corresponding lensing factor (Kneib et al. 2005), before adding these together with the appropriate weighting to create the average spectrum shown in Figure 1. The rms of this average spectrum is 11.6  $\mu$ Jy per 97.7 kHz channel, which is a factor of  $3\times$  lower than that obtained by Edmonds et al. (2009). We decide to use the more sensitive Arecibo spectrum in calculating our H<sub>2</sub>O line luminosity limits, which is plotted in Figure 1. The lensing-corrected rms of this Arecibo spectrum is 43.4  $\mu$ Jy per 97.7 kHz.

Our line luminosity limits are calculated for a range in H<sub>2</sub>O megamaser linewidths, 20, 40, 60, and 80 km s<sup>−1</sup>, consistent with that of nearby FIR luminous galaxies (Henkel et al. 2005). We then calculate lensing-corrected 3- $\sigma$  limits to the isotropic line luminosity in SMM J16359+6612,  $L_{\text{H}_2\text{O}} < 946, 1339, 1639, \text{ and } 1893 L_\odot$ . Similarly, in SMM J14011+0252 the isotropic line luminosity limits are  $L_{\text{H}_2\text{O}} < 3735, 5282, 6469, \text{ and } 7470 L_\odot$  for our assumed linewidths of 20, 40, 60 and 80 km s<sup>−1</sup>.

#### 5. Discussion

A previous search for H<sub>2</sub>O megamaser emission in SMM J16359+6612 has been conducted by Edmonds et al. (2009). While the sensitivity achieved here is nearly a factor of three higher, we do not find any evidence for line emission. Assuming a dust temperature,  $T_d = 40$  K, the corrected 850  $\mu$ m flux density of SMM J16359+6612 is consistent with a

FIR luminosity,  $L_{FIR} \sim 1.5 \times 10^{12} L_{\odot}$ , which can be used to predict the expected  $H_2O$  megamaser line luminosity according to the relationship observed in star-forming regions (Genzel & Downes 1979; Jaffe et al. 1981). The predicted line luminosity is,  $L_{H_2O} \sim 1500 L_{\odot}$ , consistent with our derived limits. In the case of SMM J14011+0252, the corrected  $850 \mu m$  flux density would imply,  $L_{FIR} \sim 6.7 \times 10^{12} L_{\odot}$ , for the same assumptions on the dust temperature. We should then expect an  $H_2O$  megamaser luminosity,  $L_{H_2O} \sim 6700 L_{\odot}$ , which is also consistent with our observed limits. If we assume the weak correlation between the  $H_2O$  megamaser luminosity and FIR luminosity measured for FIR bright galaxies by Castangia et al. (2008), we would expect megamaser line luminosities of, 3800 and 16800  $L_{\odot}$  for SMM J16359+6612 and SMM J14011+0252, respectively.

The sensitivity of our constraints on  $H_2O$  megamaser emission in these two star-forming ultraluminous infrared galaxies (ULIRGs) would suggest that they do not contain strong megamasers, such as that observed in MG J0414+0534 at  $z = 2.639$ . Although our sample size is small, these non-detections in strongly lensed, metal and gas-rich starburst galaxies would imply that strong  $H_2O$  megamaser emission may not be common among such objects. As pointed out by Edmonds et al. (2009), it is likely that the physical conditions of the interstellar gas in these predominantly star-forming SMGs is not sufficiently warm and dense to excite megamaser line emission, which is more readily excited in the X-ray irradiated environments close to a central AGN (Neufeld et al. 1994). Another possibility is that the density and temperature of the gas are large, but the gas is not sufficiently coherent in velocity with the maser source to produce strong amplification.

Weiss et al. (2005) observe multiple high- $J$  transitions of CO line emission in SMM J16359+6612, which reveal a double-peaked CO line profile, consistent with either a circumnuclear toroid of rotating molecular gas, or molecular gas associated with separate components of an on-going merger. Their excitation analysis finds the gas to be cool, with temperatures most likely below  $\sim 80$  K, while the large star-formation rate ( $\sim 500 M_{\odot} \text{ yr}^{-1}$ ) inferred by Kneib et al. (2004) should result in a high gas excitation if the CO line emission were due to a single, massive component. This low excitation gas spread over multiple components is also consistent with our non-detection of an  $H_2O$  megamaser in SMM J16359+6612.

Although our luminosity limits are consistent with what one would expect from a simple extrapolation of the  $L_{FIR} - L_{H_2O}$  relation in Galactic star-forming regions, these limits do not rule out the presence of  $H_2O$  “kilomasers” ( $L_{\odot} < 10 L_{\odot}$ ), which are typically found both within, and exterior to the nuclei of nearby star-forming galaxies (e.g. Hagiwara et al. 2001, 2003; Henkel et al. 2004). Detecting such emission in a member of the,  $S_{850\mu m} > 5$  mJy, SMG population would require hundreds of hours of observing time using the full EVLA, or Arecibo. Nearby ultraluminous infrared galaxies, which are the nearest analogues to

the high-redshift SMGs, generally do not exhibit strong water megamaser emission. The exceptions to this are NGC6240 and UGC5101 (Hagiwara et al. 2002; Zhang et al. 2006), which are both believed to contain AGN. Such an association of strong H<sub>2</sub>O megamaser emission with nearby AGN, rather than starburst ULIRGs, is consistent with our non-detections in SMM J16359+6612 and SMM J14011+0252. This would also support the original claim by Edmonds et al. (2009) that H<sub>2</sub>O megamasers will not be an effective means of measuring redshifts for starburst SMGs in future EVLA surveys.

### 5.1. Predictions for future EVLA surveys

Although we do not detect megamaser emission in the two starburst galaxies observed, the detection of an H<sub>2</sub>O megamaser in MG J0414+0534 suggests that such emission may also be present in SMGs hosting an AGN. The results of deep X-ray imaging of SMGs shows that 28–50% may harbour an AGN (Alexander et al. 2005), while the median mid-infrared spectrum of a sample of 24 SMGs (Menéndez-Delmestre et al. 2009), suggests that less than one third of the FIR luminosity is likely powered by such AGN (Pope et al. 2008). We can use these results to make simple predictions for future C-band surveys with the EVLA.

With the already existing, expanded frequency coverage of the EVLA C-band receivers, it is possible to search for water megamaser emission in  $z > 1.78$  SMGs. The forthcoming availability of the WIDAR correlator will also make it possible to obtain spectroscopy over the entire 4–8 GHz window, so that searches for redshifted megamaser emission could be conducted over the redshift range,  $1.78 < z < 4.56$ , within a field of view of 44 sq. arcmins in size. The best current constraints on the 850  $\mu$ m number counts predict about 0.1 SMGs with  $S_{850\mu m} > 6$  mJy, per sq. arcmin (Coppin et al. 2006), so that we would expect 4.4 bright SMGs in a single C-band pointing. Assuming  $T_d = 40$  K and  $\beta = 1.5$  for this sub-sample of the population, then their expected FIR luminosities would be,  $L_{FIR} > 1.1 \times 10^{13} L_{\odot}$ . Roughly 73% of the bright, radio-detected SMG population (Chapman et al. 2005), would have a redshift that places the 22.23508 GHz water maser line in the frequency interval covered by the EVLA C-band. While it may be that the 15-20% of bright SMGs with no 1.4 GHz radio counterpart are at redshifts,  $z \gg 3.5$  (e.g. Ivison et al. 2005; Wagg et al. 2009), we will assume here that all of these are at redshifts,  $z < 4.56$  (although see Coppin et al. 2009). If we make the assumption that 30% of the SMGs in this redshift range have AGN, and that 30% of their FIR luminosity is powered by this AGN, then we would expect one SMG in a single C-band pointing to have AGN with FIR luminosities,  $L_{FIR} > 3.8 \times 10^{12} L_{\odot}$ . If we assume the ratio between  $L_{FIR}$  and  $L_{H_2O}$  measured in MG J0414+0534 (Impellizzeri et al. 2008), and also that these SMGs do indeed host a water megamaser where the accretion disk is being

viewed edge-on, then they could exhibit isotropic  $\text{H}_2\text{O}$  line luminosities,  $L_{\text{H}_2\text{O}} > 40000 L_\odot$ . For the faintest, unlensed sources at  $z = 3.5$ , a maximum of 30 EVLA hours would be needed to detect the megamaser emission. However, we note that no unlensed megamaser has been detected with such an extreme luminosity, and it is possible that a cutoff in the luminosity function of  $\text{H}_2\text{O}$  megamasers exists at high luminosities. Based on their detection in MG J0414+0534, Impellizzeri et al. (2008) argue that the probability of finding an  $\text{H}_2\text{O}$  megamaser in a single, pointed observation of a high-redshift object is  $10^{-6}$  for a non-evolving line luminosity function, and 0.05 if this function evolves strongly with redshift, like  $(1+z)^4$ . Therefore, “blind” EVLA surveys for redshifted megamaser emission will serve to constrain any evolution in the luminosity function.

## 6. Summary

We have used the EVLA and Arecibo to search for  $\text{H}_2\text{O}$  megamaser emission in two strongly lensed, starburst SMGs at  $z \sim 2.5$ . The gravitational lensing of these two objects allows us to rule out the presence of strong megamaser emission, such as that observed in MG J0414+0534 at  $z = 2.639$ . We are not able to rule out the presence of kilomaser emission commonly associated with star-forming galaxies. These are the deepest limits to date on the luminosities of  $\text{H}_2\text{O}$  megamasers in high-redshift galaxies.

It is possible that future C-band surveys with the EVLA will detect one  $\text{H}_2\text{O}$  megamaser emitting SMG within a single, EVLA pointing. Currently planned EVLA observations of SMGs with observed AGN characteristics, and existing CO emission line data, will allow us to better assess the success rate of conducting such “blind” megamaser surveys in the future. At the time of completion, the EVLA will have been outfitted with new X-band (8-12 GHz) and Ku-band receivers (12-18 GHz), so that it will also be possible to conduct searches for  $\text{H}_2\text{O}$  megamasers at lower redshifts.

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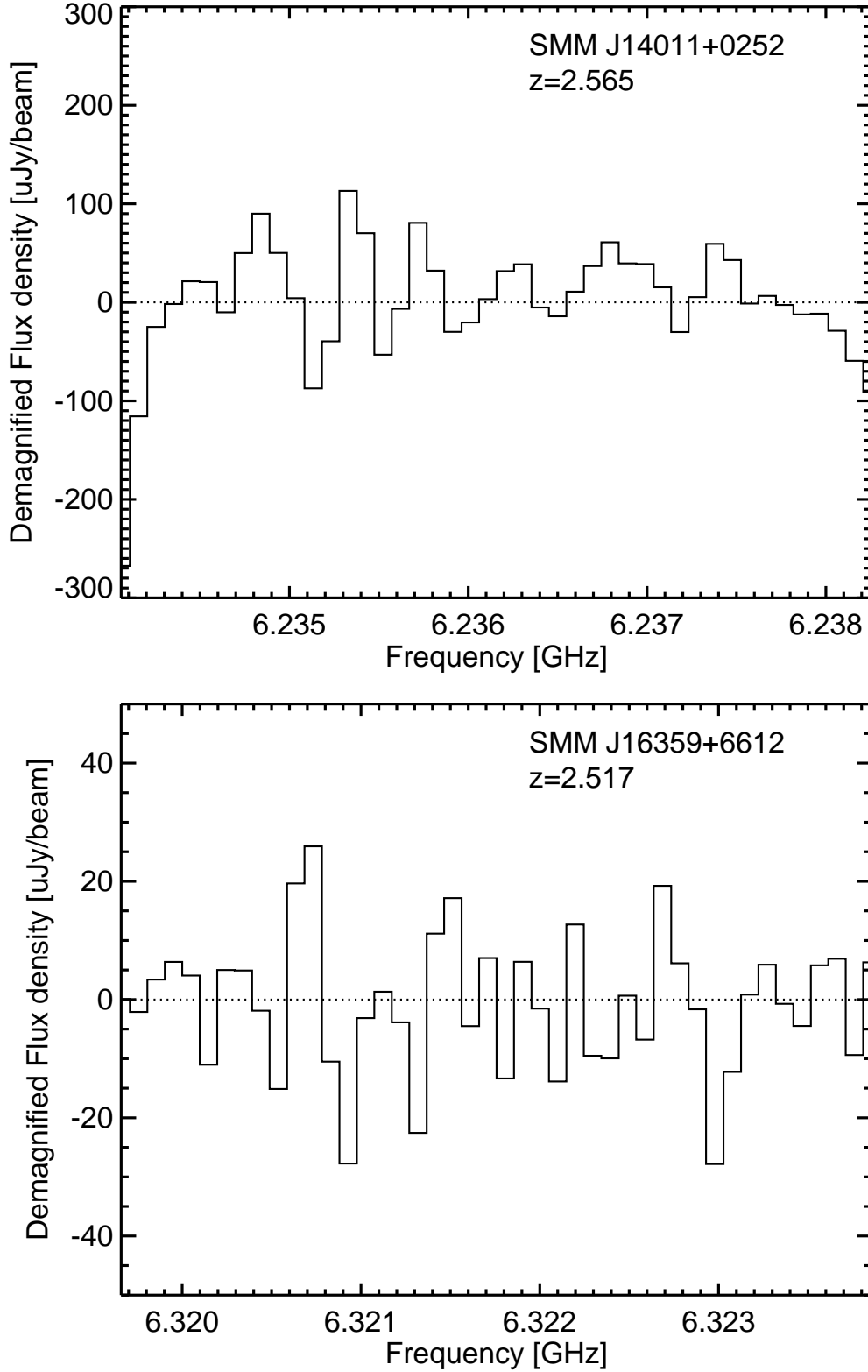


Fig. 1.— *top*: C-band high Arecibo spectrum of SMM J14011+0252 covering 6.25 MHz with a spectral resolution of 97.7 kHz and corrected for amplification by gravitational lensing. *bottom*: Spectrum of the C-band emission from the 3 lensed components of SMM J16359+6612, averaged after correcting each for the appropriate magnification factor. The original bandwidth used is 6.25 MHz with a spectral resolution of 97.7 kHz.

Table 1. H<sub>2</sub>O observations of SMM J16359+6612 and SMM J14011+0252.

	SMMJ16359	SMMJ14011
$z_{CO}$ :	2.517	2.565
Frequency:	6.3221 GHz	6.2365 GHz
Pointing center (J2000) RA:	16 <sup>h</sup> 35 <sup>m</sup> 44 <sup>s</sup> .15	14 <sup>h</sup> 01 <sup>m</sup> 04 <sup>s</sup> .92
Dec:	+66 <sup>o</sup> 12 <sup>m</sup> 24 <sup>s</sup> .0	+02 <sup>o</sup> 52 <sup>m</sup> 25 <sup>s</sup> .6
Synthesized beam:	1''70 × 1''58, P.A. 36.4°	1''80 × 1''28, P.A. 5.8°
Channel spacing:	97.7 kHz	97.7 kHz
line rms (97.7 kHz channel):	221 $\mu$ Jy beam <sup>-1</sup>	275 $\mu$ Jy beam <sup>-1</sup>